Wheel – Hub Drives versus Axle Drives

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Abstract

In this contribution a qualitative comparison concerning different electric traction drives for passenger cars is given.

Two main classes of such drives are presented: wheel – hub drives and axle drives with gear box with the same functionality. In addition also safety aspects are considered.

Especially for axle drives two different electrical machines are described. For the large - scale production the costs for the electric traction will be very important, therefore cost impacts are also investigated.

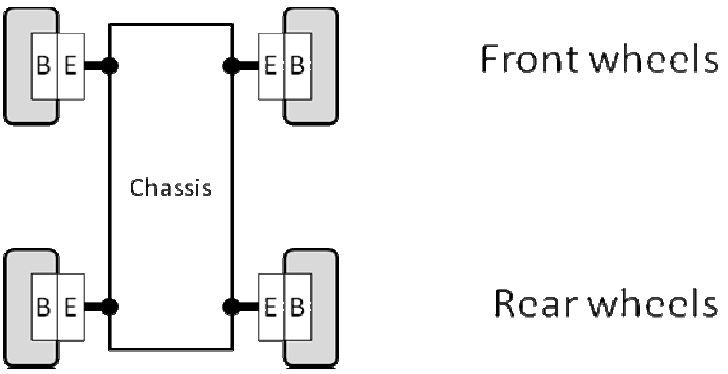
Finally a rough comparison between both drives with the same functionality will be given, resulting in the fact that the high speed drive with gear box based on an asynchronous machine will be the best solution in total.

1. Electric traction drives configurations for electric vehicles.

In this paper two electric traction drive configurations are investigated:

- wheel – hub or low – speed direct drives
- axle drives or high – speed drives with gear box

Depending on the configuration, different requirements for an electric drive will be necessary. The principal of the wheel – hub drives is shown in Figure 1.



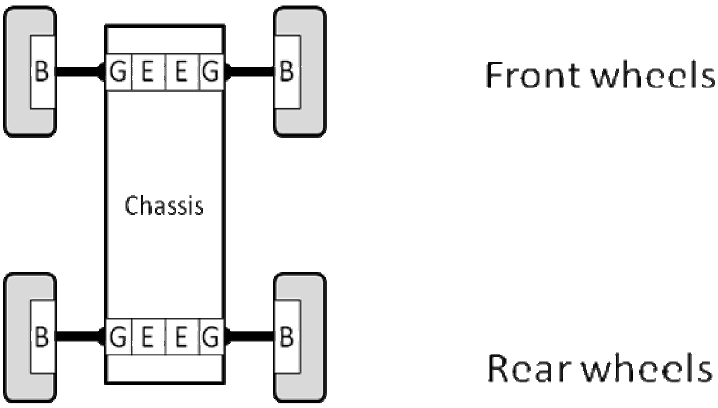
E: Electrical machine

B: Brake

Figure 1 Wheel – hub drives

Especially for passenger cars a high grade of vibration is applied to the wheel – hub drive and a high temperature caused by the brake will be transferred to the wheel – hub drive, therefore an integration of the electronic or a gear-box cannot be recommended.

The principal of the configuration with axle drives is shown in Figure 2.



E: Electrical machine

B: Brake

G: Gear - Box

Figure 2 Axle drives

For this configuration there are no special requirements concerning vibration and thermal protection for the axle drive necessary.

The question is what kind of electric drive will be the best solution concerning performance and costs. Therefore some information will be given for a rough comparison.

2. Basic mechanical equations

The wheel speed can be determined with the following equation:

$$n = \frac{V}{0.377 \cdot r} \qquad (1)$$

V = [km/h] , vehicle speed
n = [1/min], wheel speed
r = [m] , dynamic radius

If an axel drive with gear box is applied the gear ratio will be obtained:

$$i = 0.377 \frac{r \cdot n}{V} \qquad (2)$$

Example:

V = 190 km/h, r = 0,3m, (Wheel speed: n = 1700 rpm)

If we use an axle drive with a max. speed of 15.000 rpm, we obtain a gear ratio of approx 9.

Also important especially for the acceleration of the car is the torque of inertia.

With the following relation the torque of inertia can be determined

$\Theta_V = m \cdot r^2$ (3)

Θ_V = [kg m^2], torque of inertia
m = [kg], mass of the vehicle
r = [m], dynamic radius of the wheel

If a four wheel drive is required the torque of inertia related to a wheel is:

$\Theta_W = \frac{\Theta_V}{4}$ (4)

Θ_W = [kg m^2], wheel torque of inertia

By applying an axle drive with gear – box we obtain the torque of inertia related to the electrical machine shaft as follows:

$\Theta_W^* = \frac{\Theta_W}{i^2}$ (5)

i = gear- ratio

The total torque of inertia related to the shaft of the electrical machine:

$\Theta_G = \Theta_W^* + \Theta_E$ (6)

Θ_E = torque of inertia of the electrical machine

Concerning the determination of the gear ratio a second condition can be considered to obtain the optimal acceleration.

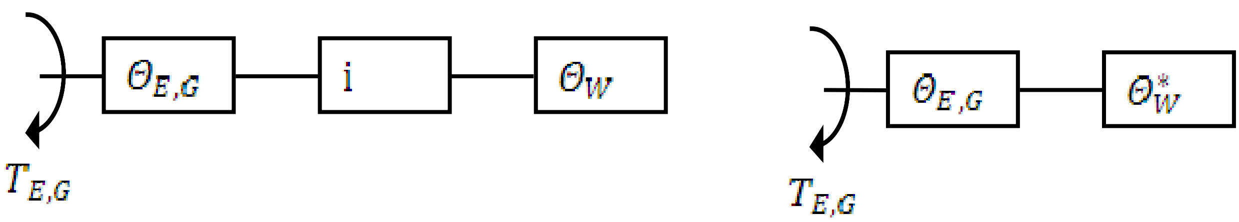
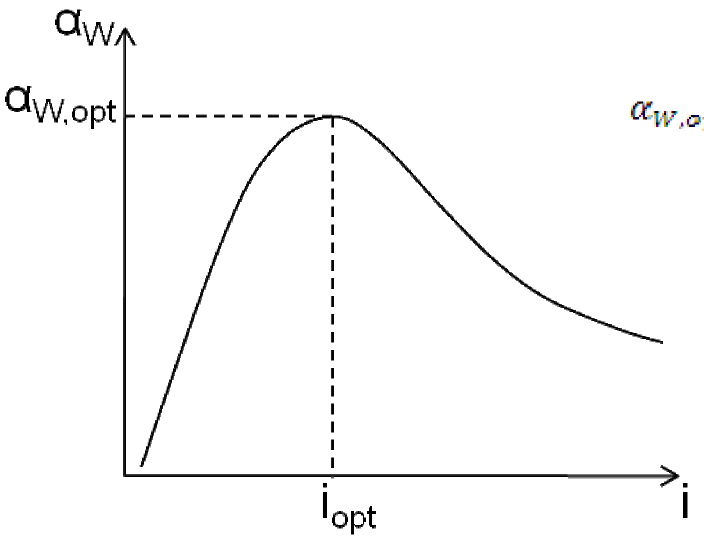


Figure 3 Mechanical model of the axle drive

$$i_{opt} = \sqrt{\frac{\Theta_W}{\Theta_{E,G}}} \qquad (7) \qquad \text{or} \qquad \Theta_W^* = \frac{\Theta_W}{i_{opt}^2} = \Theta_{E,G}$$

This equation is only valid without any drive resistance during acceleration.

With a defined input torque of electrical machine we obtain the characteristic of the acceleration versus gear ratio.



$$\alpha_{W,opt} = \frac{T_{E,G}}{\sqrt{\Theta_W \cdot \Theta_{E,G}}}$$

Figure 4 **Characteristic of acceleration versus gear ratio**

3. Main dimensions of electrical machines

3.1 Basic equations

For a defined power of an electrical machine the main dimensions of the electrical machine can be achieved with the following equations [1]:

- Diameter of the rotor

$$D = \sqrt[3]{\frac{P \cdot 2 \cdot p}{n \cdot C \cdot \pi \cdot \lambda}} \qquad (8)$$

- Active length of the machine

$$l = \lambda \cdot \frac{\pi \cdot D}{2 \cdot p} = \lambda \cdot \tau_p \qquad (9)$$

l = length of the machine

n = machine speed

p = number of pole pairs

D= diameter of the rotor

P= power of the machine (inner)

λ= ratio length to pole pitch

τ_p= pole pitch

C= utilization number

Further following relations are valid if the ratio λ will be remaining constant [1]:

- Mass of the machine

$$m \sim D^2 \cdot l \sim D^3 \qquad (10)$$

- Torque of inertia

$$\Theta \sim m \cdot D^2 \sim D^5 \qquad (11)$$

The torque of an electrical machine in general can be determined with the following equation [2]:

$$T = \pi \cdot \delta \cdot D \cdot l \cdot \frac{D}{2} \qquad (12)$$

For an axle drive:

$$T_{E,G} = \pi \cdot \delta \cdot D_G \cdot l_G \cdot \frac{D_G}{2} \qquad (13)$$

$T_{E,G}$ = input torque, δ = specific tangential force

$$T_W = i \cdot T_{E,G} \qquad (14)$$

T_W = torque at the wheel

For a direct drive:

$$T_{E,D} = T_W = \pi \cdot \delta \cdot D_D \cdot l_D \cdot \frac{D_D}{2} \qquad (15)$$

3.2 Equations for a comparison

If we introduce the factor $\beta = l/D$ as the ratio between the active length of the machine and the rotor diameter we obtain the relation concerning ratio of the diameter of the axle drive with gear – box and the direct drive.

$$\frac{D_{E,G}}{D_{E,D}} = \sqrt[3]{\frac{\beta_D}{\beta_G} \cdot \frac{1}{i}} \qquad (16)$$

$D_{E,G}$ = Diameter of the electrical machine with gear-box
$D_{E,D}$ = Diameter of the electrical of the direct drive

with $\beta_D = l/D_D$, $\beta_G = l/D_G$

Assumption of the efficiency of the gear - box: $\eta_G \approx 1$

If we remain the ratio between rotor inner diameter to rotor outer diameter constant we obtain also the equation concerning the ratio of the torque of inertia of different drives.

$$\frac{\Theta_{E,G}}{\Theta_{E,D}} = \sqrt[3]{\left(\frac{\beta_D}{\beta_G}\right)^2} \cdot \sqrt[3]{\frac{1}{i^5}} \qquad (17)$$

4. Estimation of the weight of a low–speed direct drive and high–speed drive including gear-box

For a rough estimation it is possible to use a torque versus weight characteristics published in [3].

The characteristic is valid for the following assumptions:

- Outer rotor PSM air-cooled for the low-speed direct drive
- Inner rotor PSM water cooled for the high speed drive with gear box. For the planetary gear-set a specific weight of 0, 05 kg / N_m regarded and an efficiency of 98, 5 % of the gear- box is assumed.

$$m_{GB} = 0.05 \cdot T_w \qquad [kg] \qquad (18)$$

In Figure 5 the characteristics are shown:

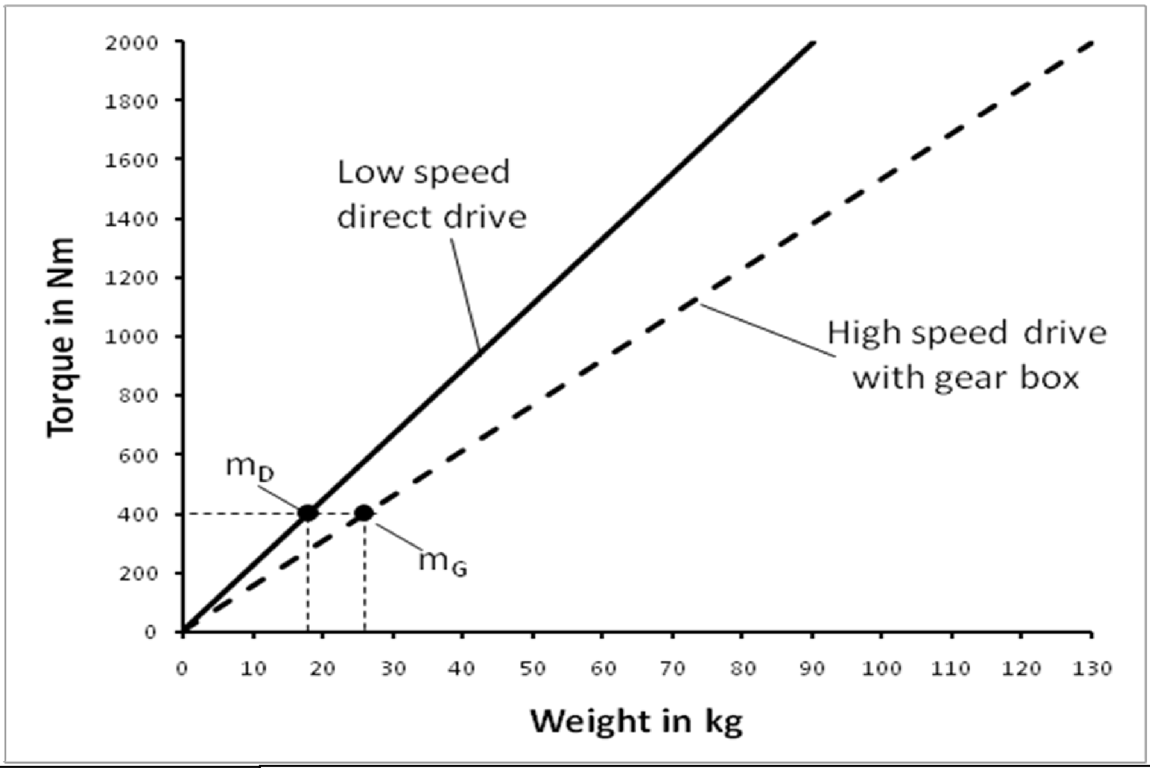


Fig.5	**Torque versus weight characteristics of different drives related to one wheel**

Because this comparison is related to one wheel (single drive), we have to multiply the weight with 4 for an all wheel drive.

Concerning weight it seems, that the low-speed direct drive will be the better solution with the regarded assumptions. To do a total comparison the costs for the mass production are very important.

Therefore we also have to compare the active material weight of the low-speed and the high-speed electrical machine.

The above named weight can be obtained with the following equation:

$$m_{E,G} = m_G - m_{GB}$$

$$= m_G - 0.05 \cdot T_w$$

For example: $T_w = 400\,Nm$

$m_G = 27$ kg

$m_D = 18$ kg $= m_{E,D}$

$m_{GB} = 0.05 \cdot 400 = 20$ kg

$m_{E,G} = m_G - m_{GB} = 27$ kg - 20 kg = 7 kg

The difference of active material is approx. 11kg (18kg-7kg) and the difference of the active and passive material is approx 9kg (27kg-18kg) related to one wheel.

In consideration, that the active material costs of an electric machine (magnets, copper, sheet metal) is much more expensive compared to the passive material of the gear-box, it can be expected, that the cost of the low-speed direct drive is more expensive in total than the high – speed drive with gear-box.

5. Electrical machines for electric vehicles

5.1 General requirements on electric machines integrated into the powertrain

Electric machines integrated into the powertrain have to fulfill the following requirements:

- low cost
- low weight / small installation space
- high efficiency
- long durability / low wear
- high availability
- low influence in case of failure
- low noise and vibration level
- high grade of protection

Besides these general requirements the further special requirements vary regarding performance, torque- and speed range depending on the installation location of the electric machine within the drive train of the vehicle. The installation location has in addition a strong influence on the frequency distribution of the operation points of the machines in the torque-speed characteristic.

5.2 Three-phase machines

Electrical three-phase current machines are particularly suitable for use in electric vehicles. [4]

The corresponding machines are combined in Figure 6.

Three-phase machine		
Asynchronous machine	**Synchronous machine**	
with cage rotor	**with permanent magnet excitation**	**with separate excitation**

Fig. 6 **Three-phase machines for electric vehicles**

5.2.1 Asynchronous machine

The asynchronous machine can be safely operated, practically maintenance-free and very well known regarding their operating behavior and industrial engineering. It can be produced at a reasonable price and therefore fulfills the important demand for economy for use in electric vehicles. Broader advantages are high rotational speeds and automatic transition to the field weakening range.

These advantages are in contrast to the known disadvantages. Since the magnetization is carried out via the stator, the power factor is always smaller than one. This means increased stator copper losses and a reduced efficiency especially in the lower speed range. Because of the squirrel cage winding the rotor reacts with additional losses linked to a further reduction of the efficiency. The field weakening range is limited, because the stalling torque falls squarely. In order to increase the field weakening range either an increased voltage range or machines with a low leakage reactance are required. In case of failure e.g. the control is out of range, the behavior of the asynchronous machine will not cause any problems, because the machine demagnetize itself very quickly and is running at idle speed for example. Further no over voltages will be generated.

5.2.2 Synchronous machine

Under the concept synchronous machine all machines without slip between rotor speed and stator field speed are combined. Normally the machine will be fed with a sinusoidal air gap flux and it will be distinguished by the kind of rotor excitation.

- **Permanent magnet excited synchronous machine**

This kind of machine has a very compact design and a high efficiency especially in the lower speed range. The losses appear predominately in the stator of the machine. Nevertheless this machine has also some disadvantages like limited field weakening range, the lower efficiency in the upper speed range in the partial load region, the high costs and the availability of the magnetic material. The behavior finally is not unproblematic in the fault case because the machine cannot become demagnetized. In the field weakening range "dragging losses" appear, even when the machine runs at idle speed.

- **Current excited (separate-excited) synchronous machine**

The advantages are obvious:

High field weakening range with a linearly torque reduction versus speed. High efficiency in the higher speed range, even in the partial load region because the excitation current can be reduced. With use of a self-commutated inverter an operation with power factor $\cos \varphi = 1$ will be possible through which the inverter is used optimally.

The disadvantages are related to the rotor. The production is more effortful than with the other AC-machines because an insulated copper winding must be produced and safeguarded against centrifugal force with slip rings and brushes. For wear reasons of the brushes/slip rings a speed above 10 000 rpm seems to be questionable in the higher power range of machines. The rotor losses are concentrated in few slots therefore a separate ventilation is normally needed. In addition also a field supply unit is required.

The increased effort in the rotor as well as the limitation of the speed has been the reason that the separately-excited synchronous machine has not found considerable use for electric vehicles in the practice so far.

6. Safety relevant aspects

Furthermore, as already mentioned it is imperative that no safety technical problems appear in the traffic in case of failure of the electric drive system. Beside the already mentioned unwanted over current switch offs and possible over voltages, the properties of the different electric drives have to be additionally taken into account in case of failure. Particularly the two- or three-phase short circuits at the terminal or winding earn special attention.

In series of a two or three-phase short circuit only a short time peak torque appears at the asynchronous or separately excited synchronous machine. In case of a permanent excited synchronous machine in addition of the peak torque a stationary break torque also appears depending on the speed. The braking power will be in a range of 10% of the nominal power because the short circuit current will be in the range of the nominal current. In case of a two-phase short circuit in addition to the short-time peak torque, an oscillating torque depending on speed will appear and can excite the mechanical drive train.

With the following measure it is possible to avoid safety problems:

- Disconnecting the mechanical drive train by a fast switching clutch.

In particular from today's point of view a mechanical brake system cannot be replaced.

7. Electric traction based on wheel-hub drives – a serial proposal.

Current publications reports more or less about the functionality of prototype vehicles. In the foreground the functionality will be focused, therefore the following figure will show (one axle) proposal for mass production.

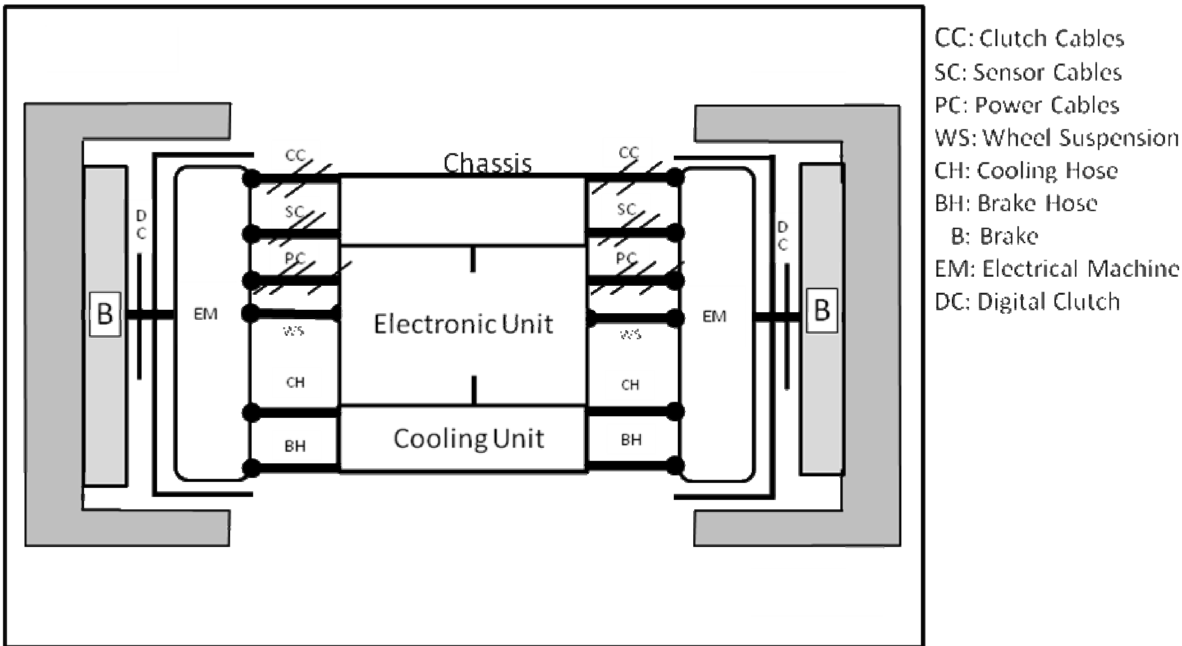


Figure ˉ	**Proposal with wheel-hub drives (one axle)**

For the electrical machines a PSM / IPM as outer rotor version will be proposed because the installation space at the wheel is very limited.

8. Electric traction based on axle drives with gear-box – a serial proposal

In the following Figure a well known axle drive for mass production is shown:

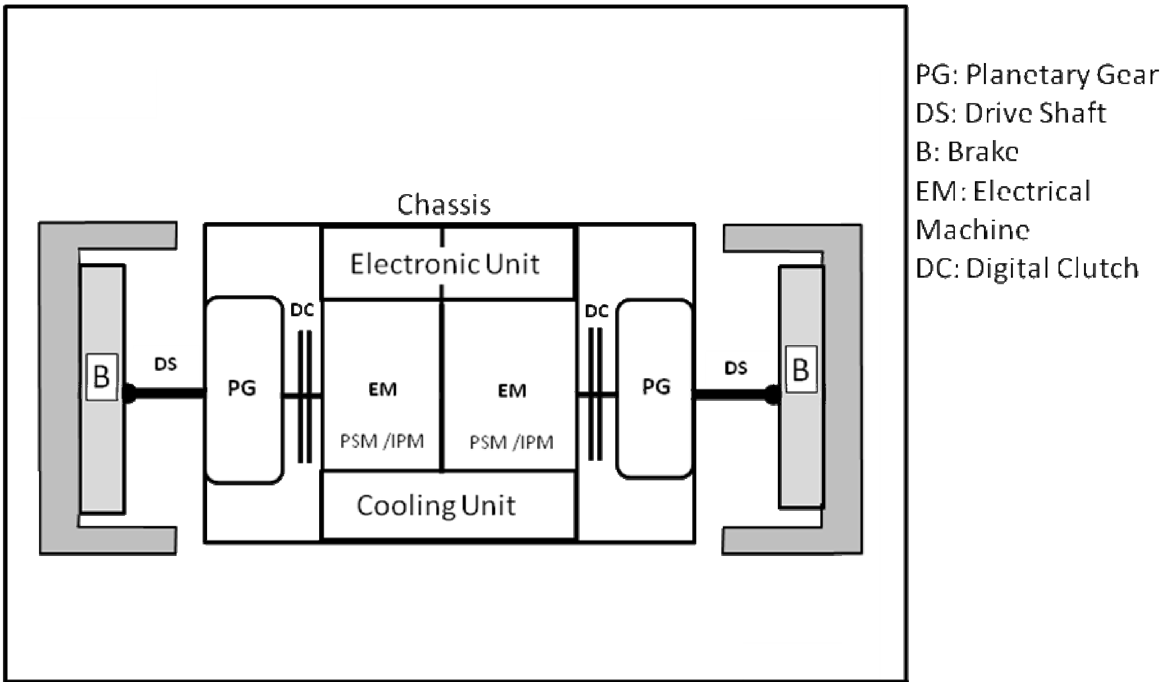
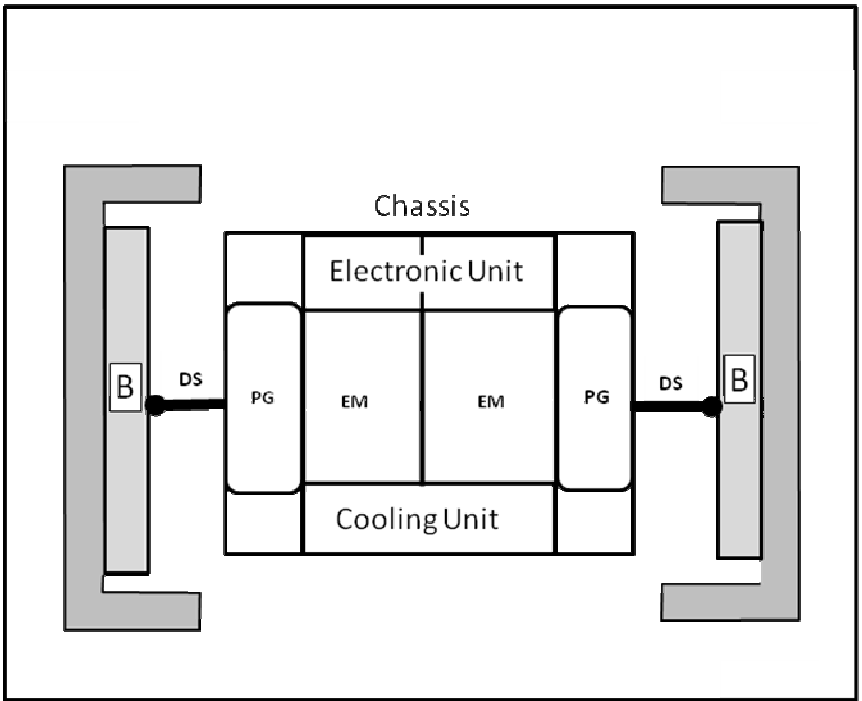


Figure 8	Proposal with axle drives by using a PSM / IPM (one axle)

The need of a digital clutch (DC) depends on the kind of the electrical machine. If we use an asynchronous or separately excited synchronous machine a digital clutch can be removed, see chapter 6.



PG: Planetary Gear
DS: Drive Shaft
B: Brake
EM: Electrical Machine

Figure 9 **Proposal with axle drives by using a asynchronous or separately exited synchronous machine. (one axle)**

Especially by using an asynchronous machine it is very advantageous to transfer the region for high efficiencies in the medium up to the high speed range of the machine via a gear-box to the required low speed range of the wheel (see Figure 10)

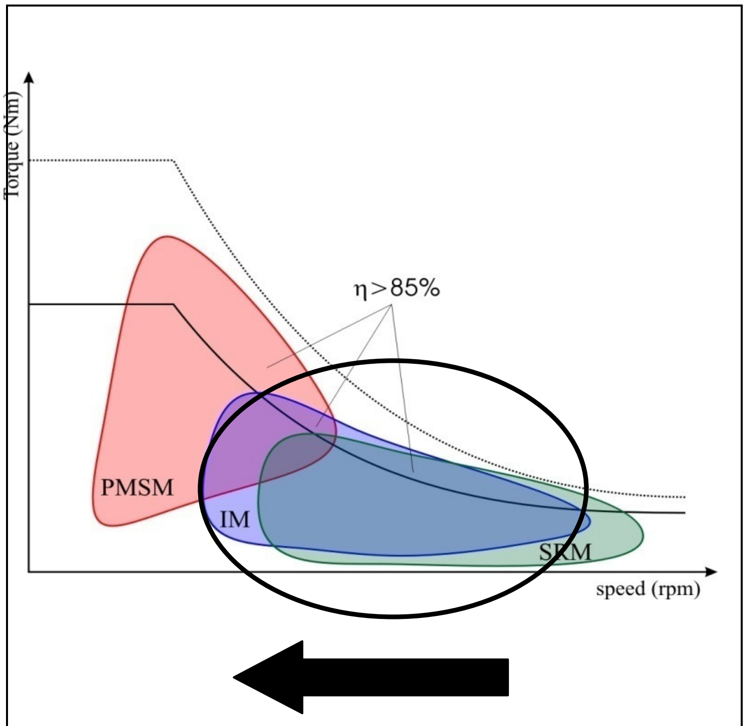


Figure 10 **Efficiency map of different electrical machines**

9. Electrical traction based on an axle drive with a two gear shift automated manual transmission (AMT)

In relation with a two gear shift simplified AMT it is possible to adapt the characteristic of the electrical machine to the required working point of the vehicle in order to active the best economical solution.

By using an AMT in relation with an internal combustion engine during the shift phase a noticeable torque interruption can be expected. But in relation with a high dynamic electrical drive without a clutch it is possible to reduce the torque interruption to an acceptable value.

Following shift procedure will be applied:

- Switch the electrical machine from speed control to the torque control mode and set the torque value at the shaft to zero.
- Disengage the old gear
- Adapt the shaft-speed of the electrical machine via speed – control to the new shaft-speed according the new gear-ratio for synchronization of the gear-wheels
- Synchronize the gear-wheels
- Engage the new gear
- Switch the electrical drive from speed control to the torque control mode and apply the requested torque value to the shaft.

With this shift procedure the time of the torque interruption can be reduced considerable compared to existing solutions.

10. Conclusion

For nice applications an electric traction based on wheel-hub drives could be an alternative to the application with axle drives, if a slightly increased installation space of the battery is required. But this solution will be the most expensive solution in total.

For the mass production in terms of cost, robustness and safety there is no alternative to an electric traction based on axle drives in relation with acceptable cost of the battery. In particular if the axle drive is based on an asynchronous machine the system will have the lowest costs.

If only the same performance is required and not the functionality (e.g. all wheel drive) a central drive, well known as transaxle drive based on an asynchronous machine will be the low cost solution in total.

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